Neutrino Physics

Tomasz Wąchała

Instytut Fizyki Jądrowej
im. H. Niewodniczańskiego
Polskiej Akademii Nauk
Kraków

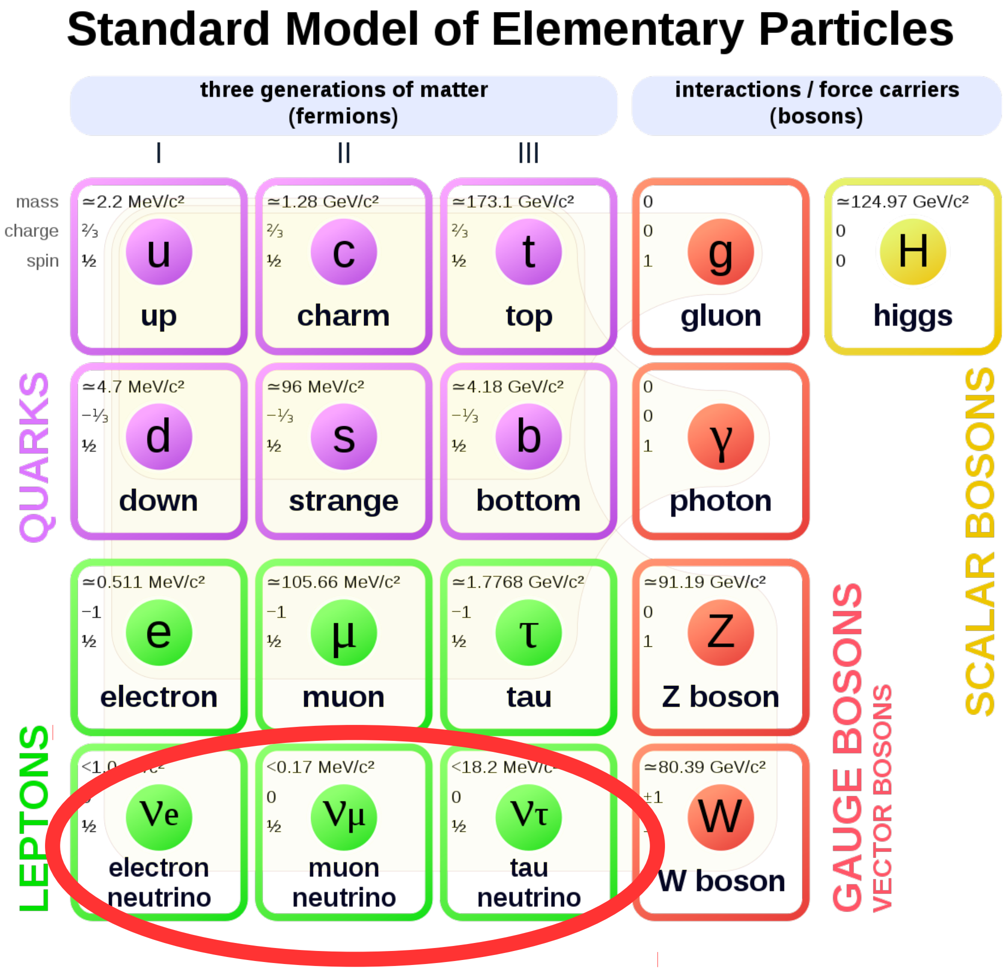
Kraków, 18.02.2021

Outline

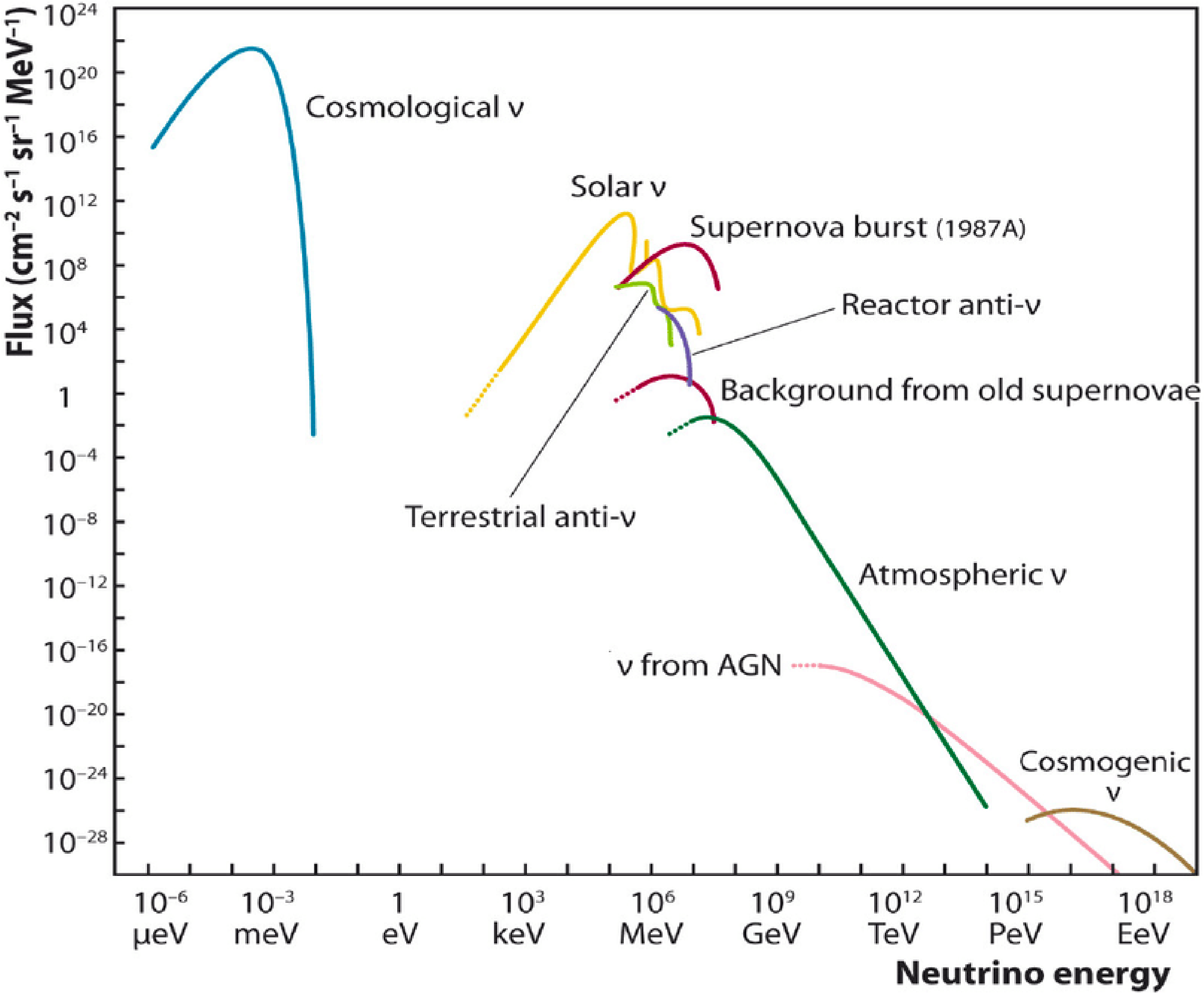
1. Neutrinos in the Standard Model
2. Relic, geoneutrinos, supernova neutrinos
3. Atmospheric neutrinos
4. Solar neutrinos
5. Neutrino oscillations

Neutrinos in the Standard Model

- Neutrinos are elementary particles with the following properties in the Standard Model of particle physics:
  - Fermions, interacting only via weak interactions
  - Neutral (no electric charge)
  - Massless
  - Come in three flavor states: electron neutrino: ν_e, muon neutrino: ν_μ, taon neutrino: ν_τ). LEP experiment results are consistent with the three neutrino flavors (Z^0 boson widht measurement).
  - Only left-handed neutrinos and right-handed antineutrinos are observed



Neutrino sources



Relic neutrinos

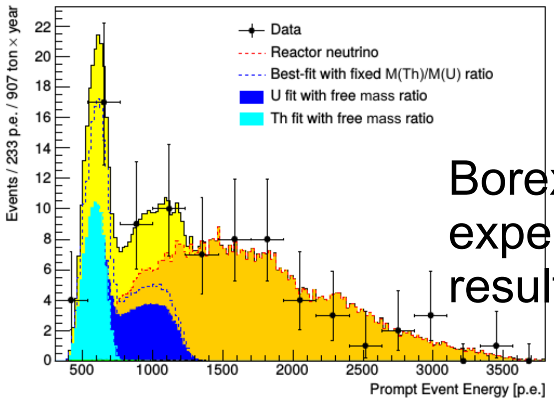
- In the early universe neutrinos were in thermal equilibrium with protons, neutrons and electrons maintained through the weak interactions.
- Production of neutrinos in the early Universe in the weak process:

$$e^{+}+e^{-}\rightarrow \nu_e+\bar{\nu}_e$$

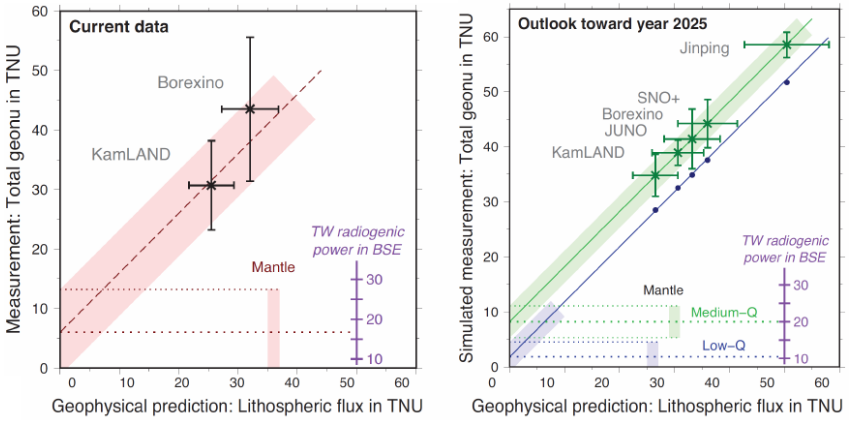
- When the rate of this reactions became smaller than the rate of expansion of the universe neutrinos exit the thermal equilibrium and and decouple from other types of matter with kT < 3 MeV at $t>10^{-2}$ s
- Average density of relic neutrinos (for 3 flavors) ~330 m^{-3}
- Temperature ~ 1.95 K
- Very low energies (~meV) therefore very difficult to measure. Not detected so far.

Geoneutrinos

- Neutrinos are produced inside the Earth by the radioactive decays of long-lived natural isotopes: Uranium (U), Thorium (Th), Potassium (K), Radium (Ra),…
- Beta decays are the source of electron antineutrinos. The flux of geoneutrinos ~ $6 \cdot 10^{6}$ cm^{-2}s^{-1}.
- Applications:
    - Geology, Geophysics. Studies of Earth's interior by measuring the fluxes of neutrinos at the surface. Studying the composition of our planet without drilling below the surface.
    - Background in many neutrino experiments (KamLand, Borexino) and future ones: SNO+, Juno.



Borexino experiment results



Lithospheric geoneutrino flux data vs predictions

Supernova neutrinos

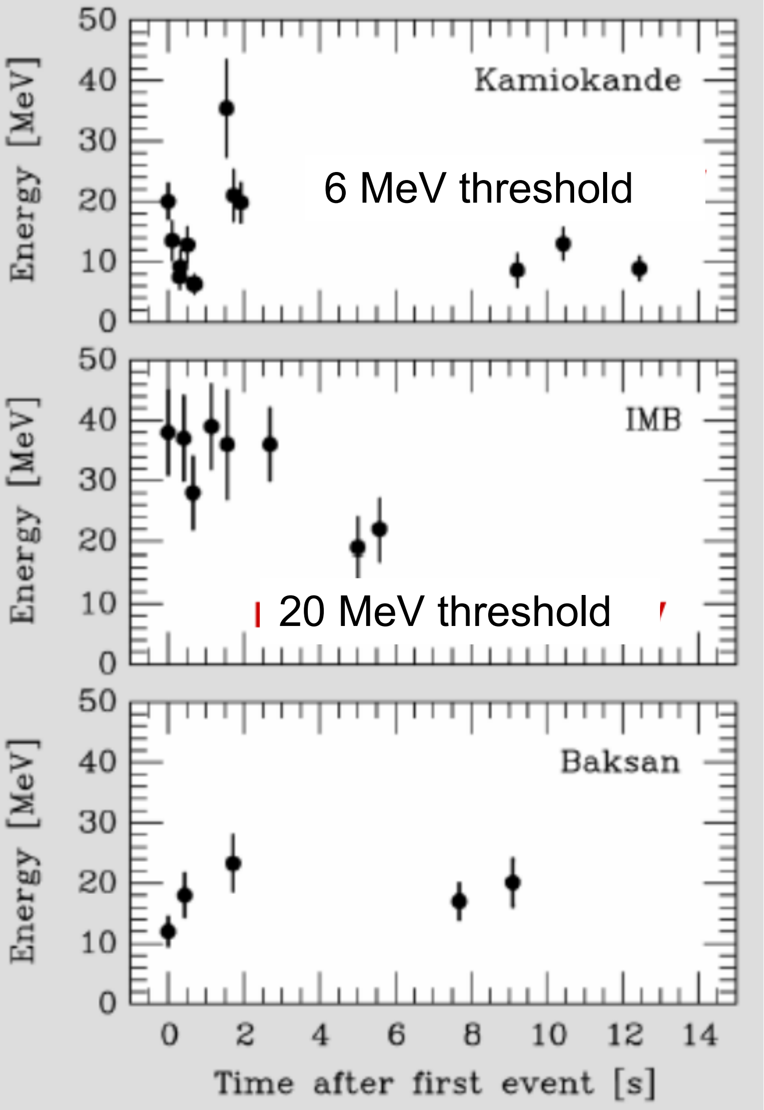
- Neutrinos are produced during the gravitational collapse of the core of the massive star (m>10M_{Sun}).
- Emmision of the neutrinos from the neutronization process (~ms): $e^{-}+p\rightarrow n+\nu_{e}$. Core density increases to nuclear matter density and neutrinos are trapped. Neutron star is borned.
- External layers fall into the core and bounce back causing a shockwave → Supernova explosion. Neutrinos are released in the shockwave.
- Neutrinos are also produced in: $e^{+}e^{-}\rightarrow Z^{0}\rightarrow\nu_{e}+\bar{\nu}_{e},\nu_{\mu}\bar{\nu}_{\mu},\nu_{\tau}\bar{\nu}_{\tau}$

Supernova neutrinos

- During the neutron star cooling:
  - 99% of the gravitational energy is emmited in the form of neutrino pulse lasting several seconds (~10^{58} neutrinos)
  - 1% is a kinetic energy of the explosion
  - 0.01% photons
- Main detection channel:

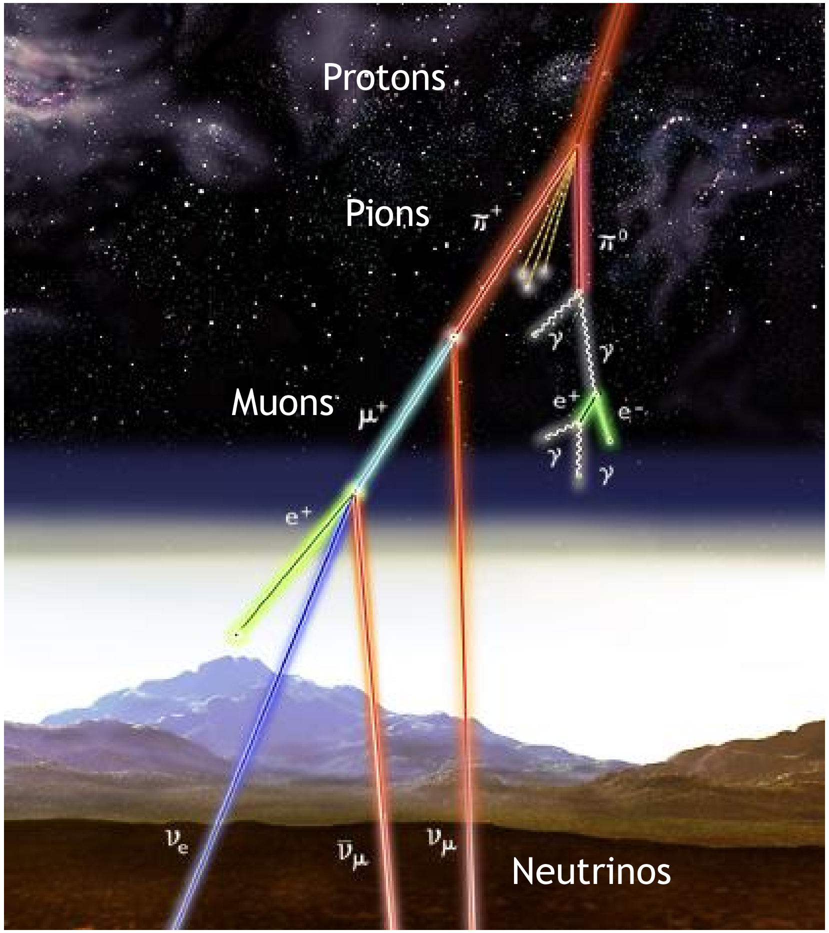
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- Kamiokande (Japan), IMB (USA) water Cherenkov detectors and Baksan (USSR) scintillation detector measured the electrons from Supernova 1987A neutrinos with energy ~10-15 MeV



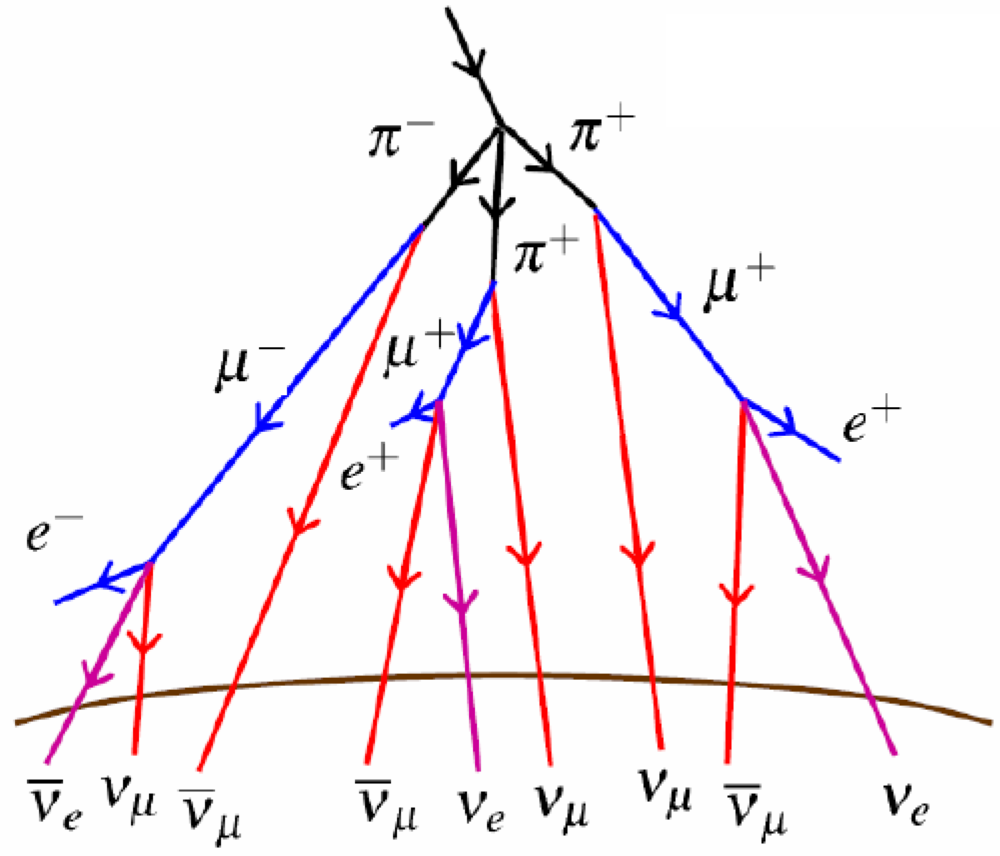
Supernova 1987A observation

Atmospheric neutrinos



- Primary cosmic rays - very high energy (even 10^{20} eV) particles (86% of protons) interact with the nuclei in the higher parts of the atmosphere producing secondary particles, mainly pions.
- Charged pions decay into muons and muon neutrinos
- Muons decay into positons and electron neutrinos
- Atmospheric neutrino flux ~1 cm^{-2} s^{-1}
- Mean energy of atmospheric neutrinos ~ 1 GeV (MPV ~100 MeV)

Muon/electron neutrinos ratio



- The ratio of number of muon neutrinos and antineutrinos to number of electron neutrinos and antineutrinos below 1 GeV should be equal approximately 2

$$\frac{N_\mu}{N_e} = \frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$

- Experimentally it is convenient to estimate double ratio R to reduce the systematic uncertainties. It is defined as observed ratio / theoretical ratio.

$$R = \frac{(N_\mu / N_e)_{Obs}}{(N_\mu / N_e)_{Teor}}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\llcorner\ e^+ + \nu_e + \bar{\nu}_\mu \qquad \llcorner\ e^- + \bar{\nu}_e + \nu_\mu$$

Atmospheric neutrinos anomaly

- In the 1980s several experiments reported a deficit in the number of detected atmospheric muon neutrinos
  - IMB (USA, 1986):
  - Kamiokande (Japan, 1988):

$$\boxed{\begin{array}{l} R = 0.54 \pm 0.05 \pm 0.12 \\ R = 0.60 ^{+0.06}_{-0.05} \pm 0.05 \end{array}}$$

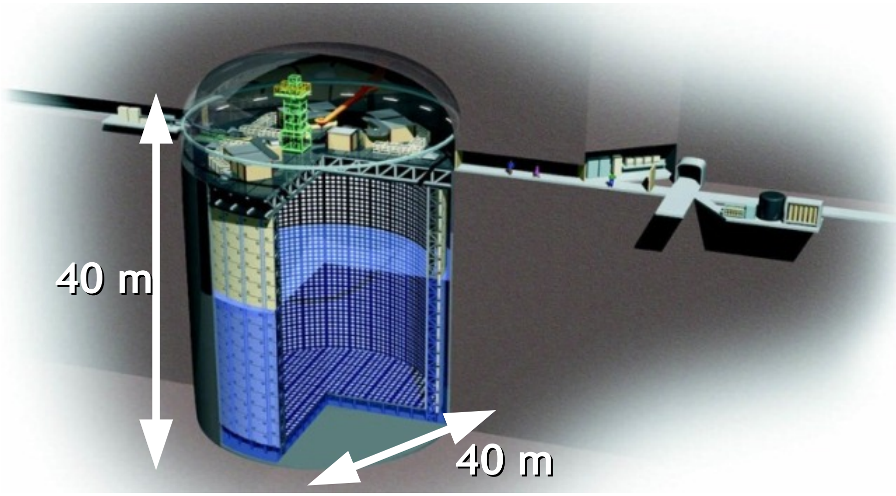
- ...on the other hand there were experiments that didn't observe any deficit:
  - Frejus (Francja, 1989):
  - NUSEX (Francja/Włochy, 1982):

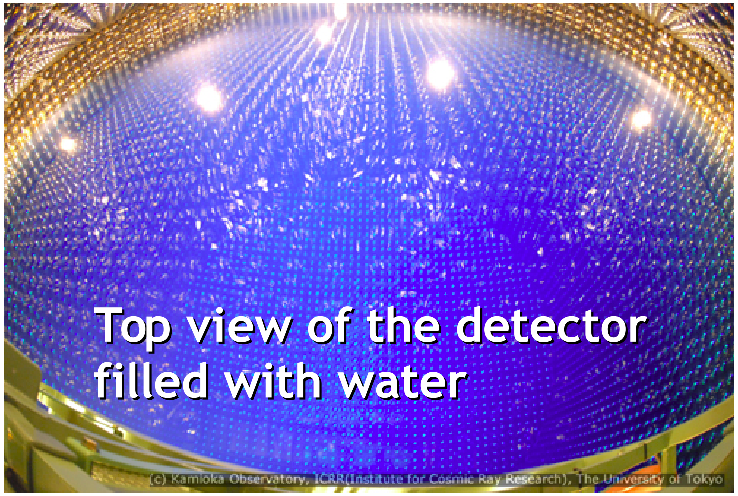
$$\boxed{\begin{array}{l} R = 1.00 \pm 0.15 \pm 0.08 \\ R = 0.99 ^{+0.35}_{-0.25} \end{array}}$$

- No final conclusion...

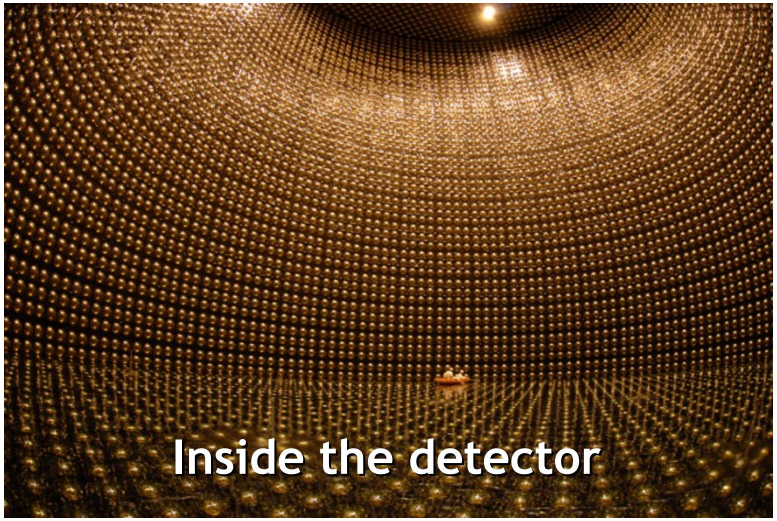
Super-Kamiokande experiment

- ...until Super-Kamiokande came into the game. World largest neutrino detector (operating since 1996):
  - Cylindrical tank with the diameter and height of 40m,
  - 1kilometer underground, in the Zinc mine Mozumi in Japan
  - Tank filled with kton of ultra pure water
  - 11 000 of photomultipliers on the walls of the tank detecting Cherenkov light produced by charged particles

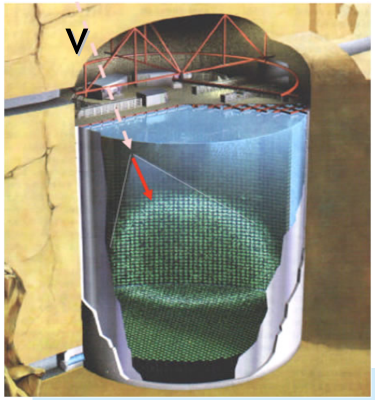



Top view of the detector filled with water

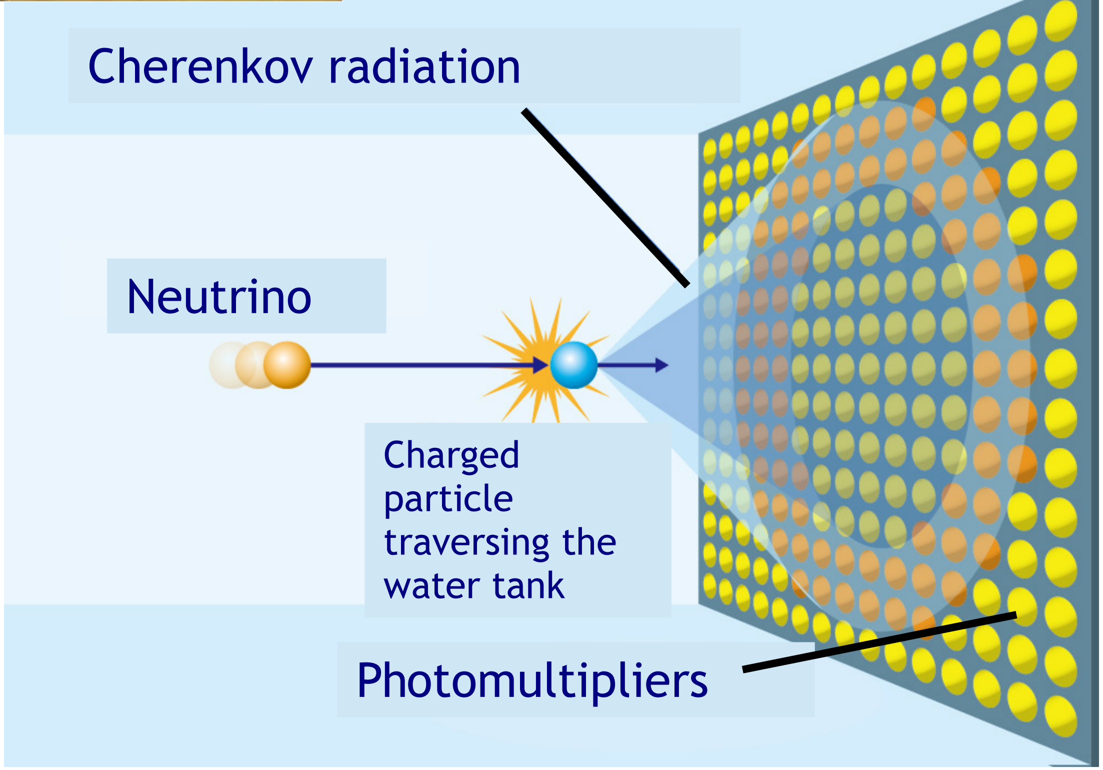
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo


Inside the detector

How Super-Kamiokande „sees” neutrinos?



- Neutrinos interact with the oxygen nuclei inside the tank and produce charged particles



Cherenkov radiation

Neutrino

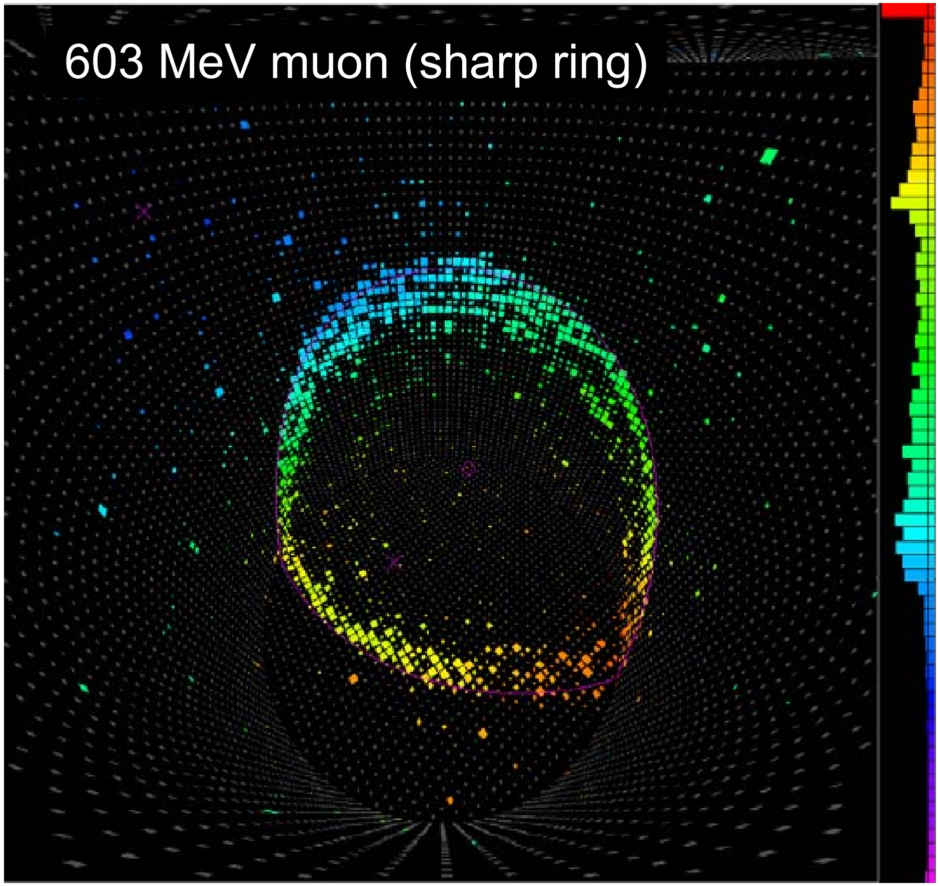
Charged particle traversing the water tank

Photomultipliers

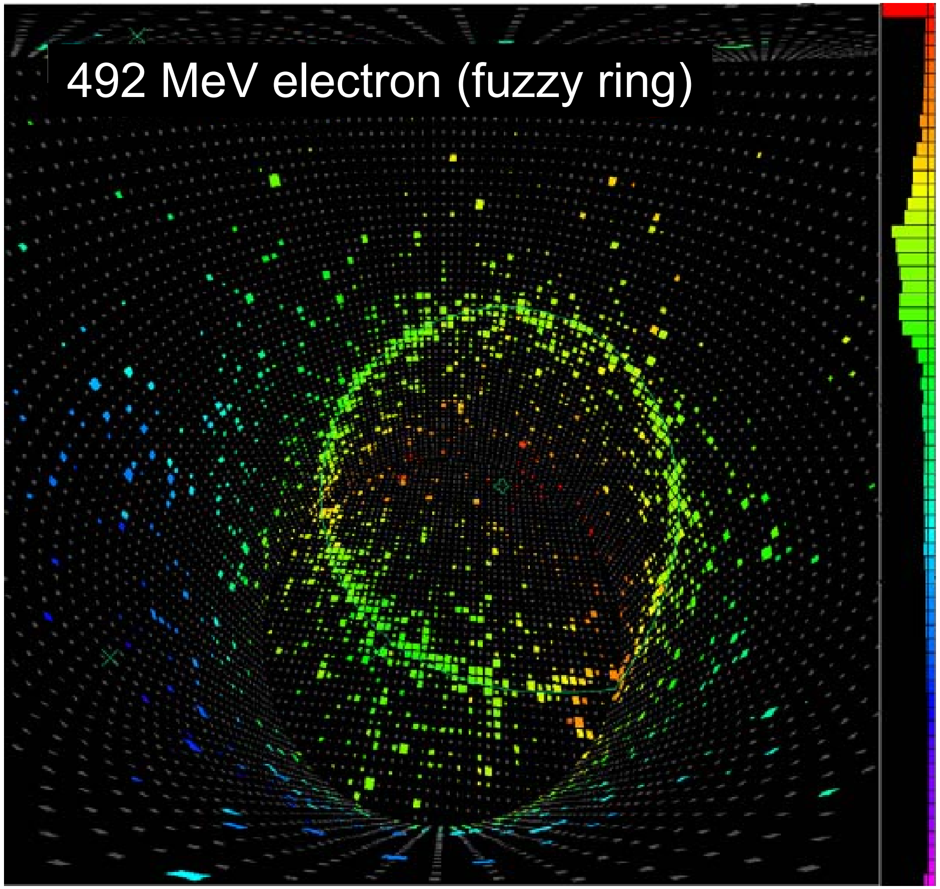
- Charged particles travelling in the medium (eg. Water) faster than the speed of light emit photons of the Cherenkov light along their trajectory
- Photomultipliers detect the characteristic rings of the Cherenkov radiation
- Spatial and the time distribution of the Cherenkov light allow to reconstruct the direction of charged particle (and neutrino direction)
- Amplitude of the signal, the opening angle of the cone and characteristic pattern of ring allow to discriminate between muons and electrons and measure their energy

How Super-Kamiokande „sees” neutrinos?

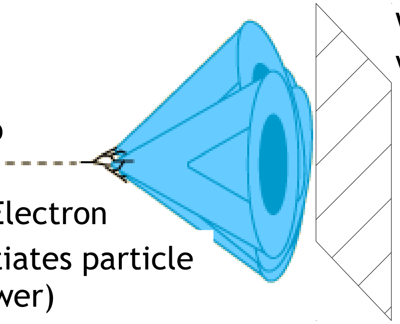
$\nu_\mu + n \rightarrow \mu^- + p$



$\nu_e + n \rightarrow e^- + p$



Atmospheric neutrinos in Super-Kamiokande

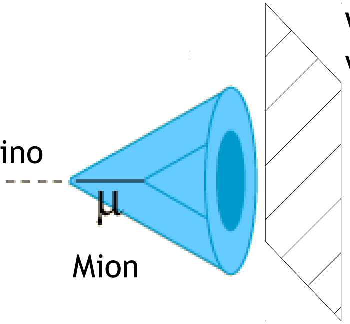


Electron neutrino

Electron

(initiates particle shower)

Wall of the detector with photomultipliers

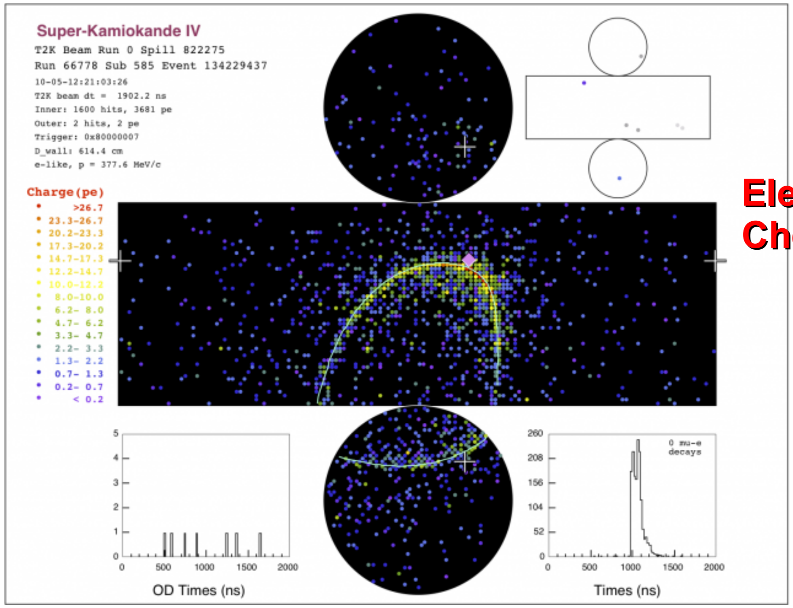


Muon neutrino

μ

Mion

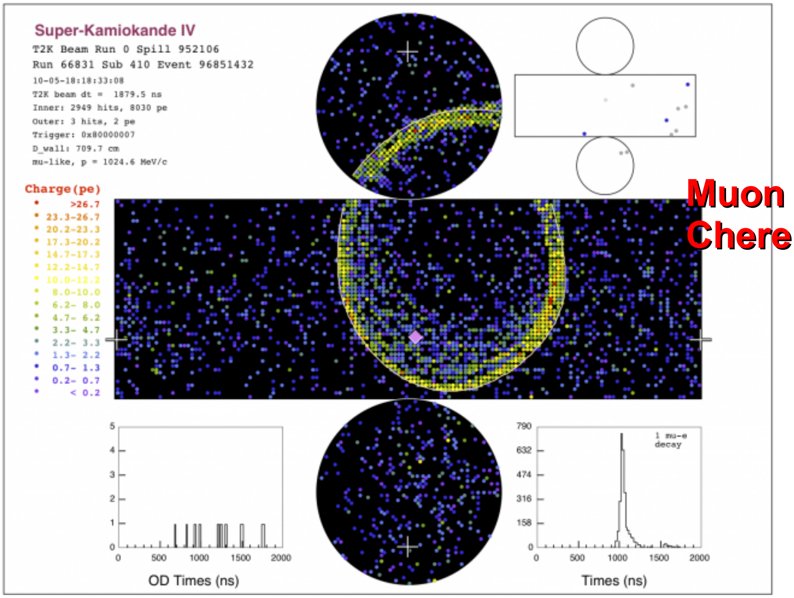
Wall of the detector with photomultipliers



Super-Kamiokande IV

```
T2K Beam Run 0 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:26
T2K beam dt =  1902.2 ns
Inner: 1600 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 377.6 MeV/c
```

Electron-induced Cherenkov ring



Super-Kamiokande IV

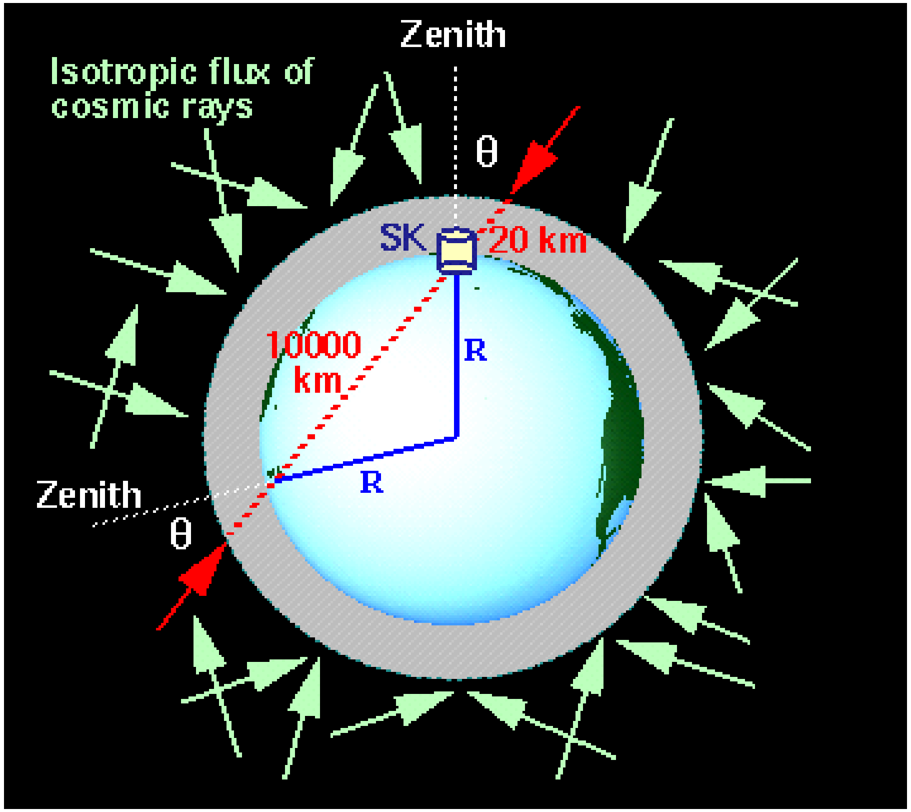
```
T2K Beam Run 0 Spill 952106
Run 66831 Sub 410 Event 96851432
10-05-18:18:33:08
T2K beam dt =  1879.5 ns
Inner: 2949 hits, 8030 pe
Outer: 3 hits, 2 pe
Trigger: 0x80000007
D_wall: 709.7 cm
mu-like, p = 1024.6 MeV/c
```

Muon induced Cherenkov ri

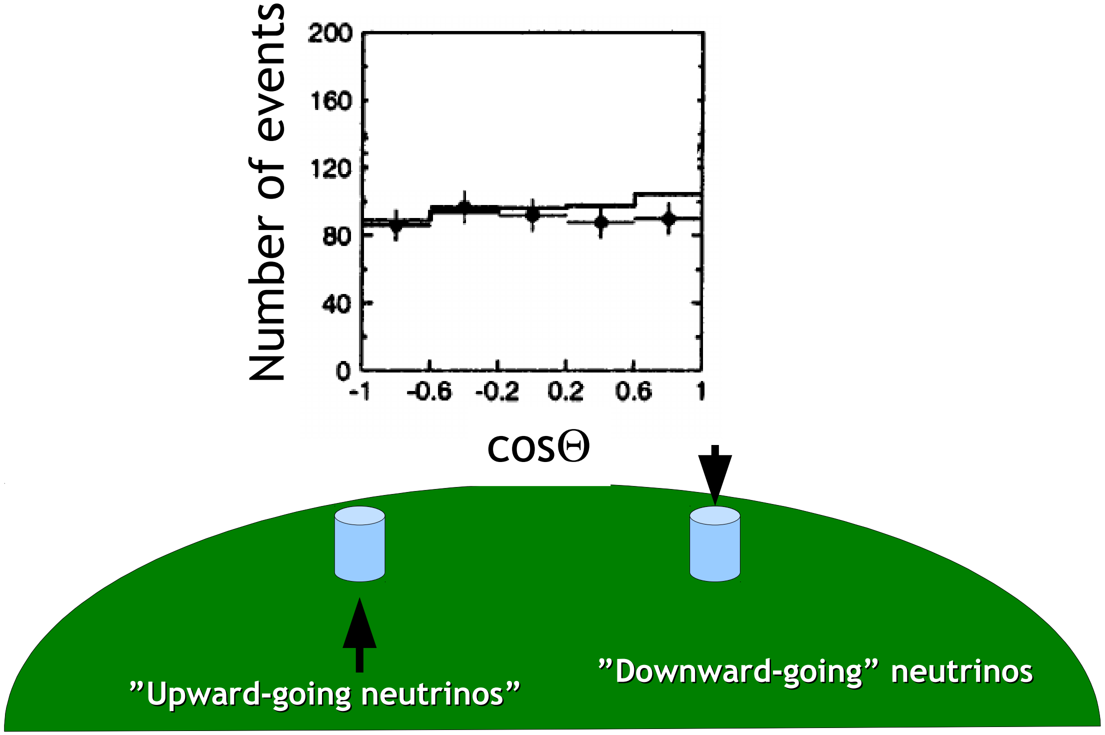
- Super-Kamiokande online event display:

http://www-sk.icrr.u-tokyo.ac.jp/realtimemonitor/

Zenith angle dependence



- The flux of atmospheric neutrinos should be isotropic. The ratio of the number of ”upward-going” and ”downward-going” muons from atmospheric neutrinos should be equal 1.
- Zenith angle Θ measures the length of the trajectory of neutrino from the production point to the detector



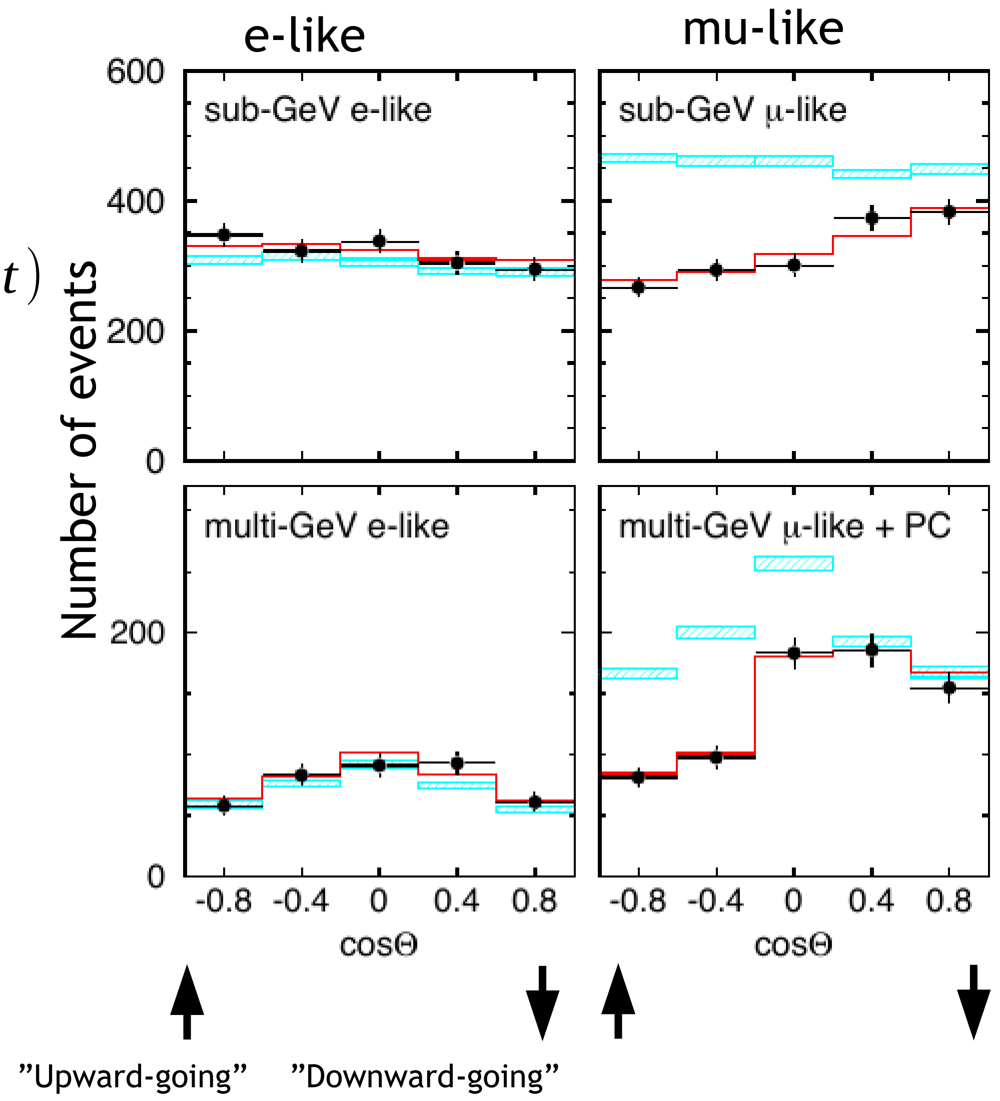
Super-Kamiokande results (1998)

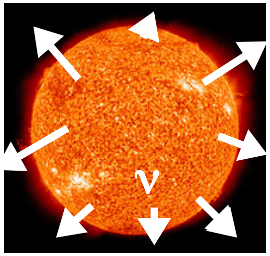
- After two years of data taking (1996-1998) experiment reports:

$$R=\frac{(N_{\mu}/N_{e})_{Obs}}{(N_{\mu}/N_{e})_{MC}}=0.63\pm0.03(stat)\pm0.05(syst)$$

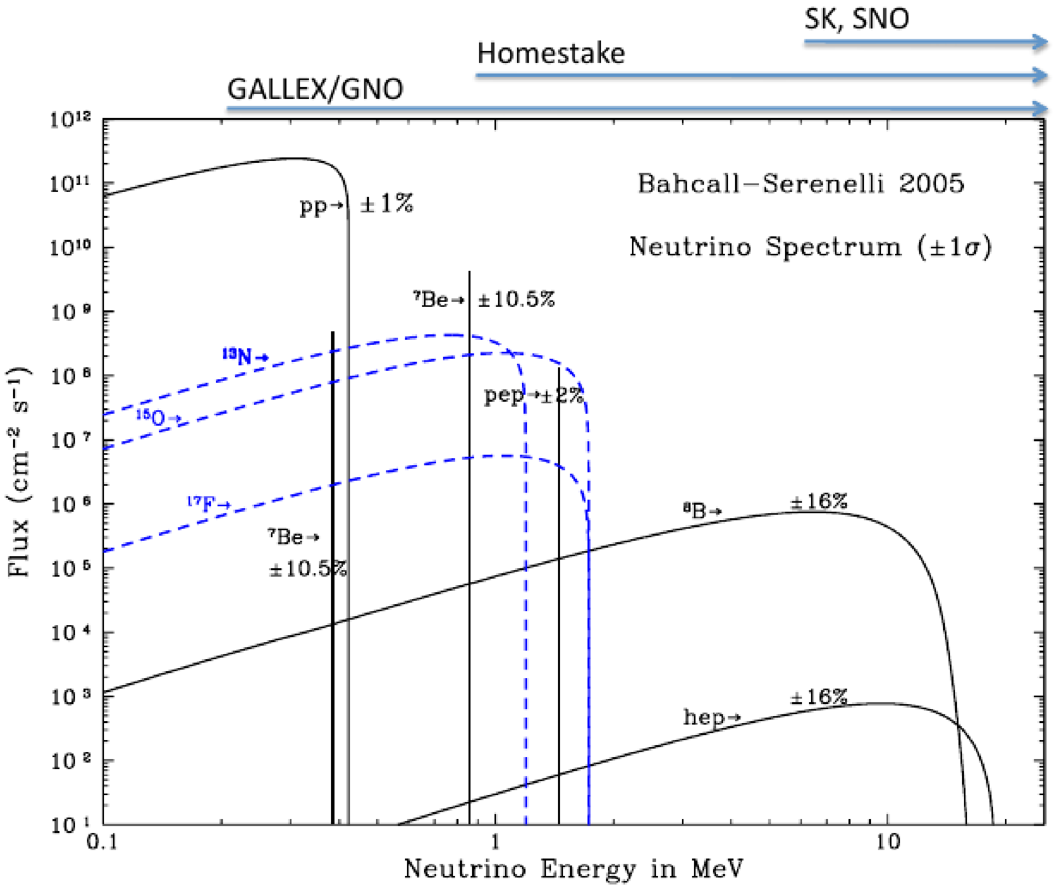
- Observed ratio wrt theoretical ratio is close to 2/3 (muon neutrino deficit).

- There’s a dependence of the number of muon neutrinos on the length of the trajectory. There’s larger deficit of ”upward-going” (cosΘ ~ -1) wrt theoretical predictions.





Solar neutrinos

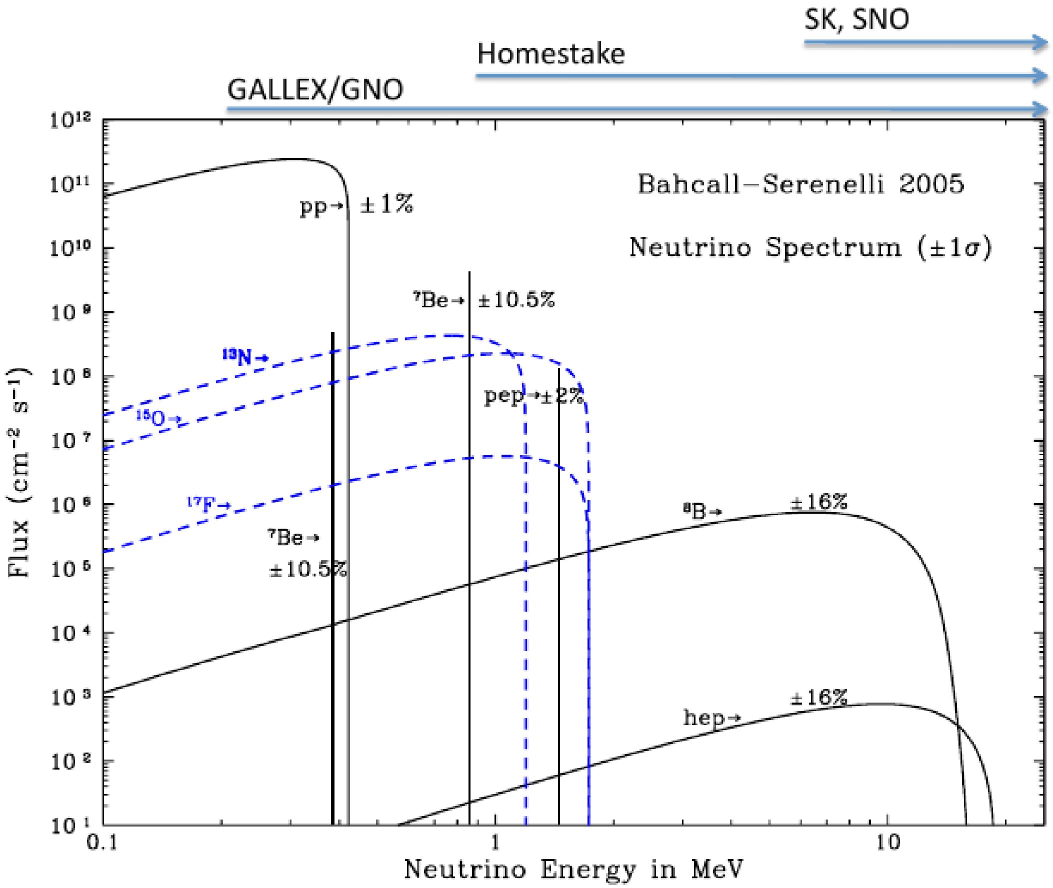


Most of the solar neutrinos come from:

$$4\,p \rightarrow {}^{4}He+2e^{+}+2\nu_{e}+2\gamma$$

- Electron neutrinos are produced in the Sun in the thermonuclear reactions:
  - pp and CNO cycle
  - Electron capture on ^{7}Be
  - Beta decay of ^{8}B
- Overall flux of solar neutrinos on earth: 6.5×10^{10} cm^{-2} s^{-1}
- Theoretical predictions come from the well established Standard Solar Model (SSM) developed since 1963 and continously updated by J. Bahcall et.al. over a several decades.

Solar neutrinos - detection methods



Radiochemical:

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \qquad \nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Water Cherenkov:

$$\nu_X + e^- \rightarrow \nu_X + e^- \qquad \nu_X + n \rightarrow \nu_X + n$$

- Low energy ν_e - radiochemical experiments (Ga, Cl) GALLEX, GNO, Homestake:
  - Low energy threshold
  - Only counting nuclei in the final state of the reaction
  - No information about the time of interaction
  - No information about neutrino direction

- Neutrinos with Eν>5 MeV – Water Cherenkov detectors - Super-Kamiokande, SNO:
  - Higher energy threshold
  - Neutrino time and direction information available

Solar neutrino puzzle

- 1969 – 1999 – Davis experiment in the Homestake mine in USA was constantly reporting a deficit of solar neutrinos.
  - Measured flux: 2.56 ± 0.16 (stat) ± 0.16 (sys) SNU
  - Predictions: 8.5 ± 0.9 SNU
- 1992-2010: GALLEX/GNO experiment in Italy and SAGE (USSR): observed ~50% lower solar neutrino flux than predicted by SSM
- 1989: Kamiokande experiment in Japan observed ~50% lower solar neutrino flux

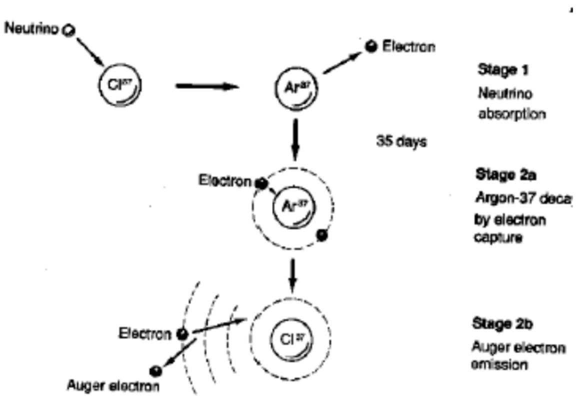
Three options:

SSM is wrong, experiments don't control well their systematic errors or something is happening with the neutrinos during their travel from Sun to the the Earth

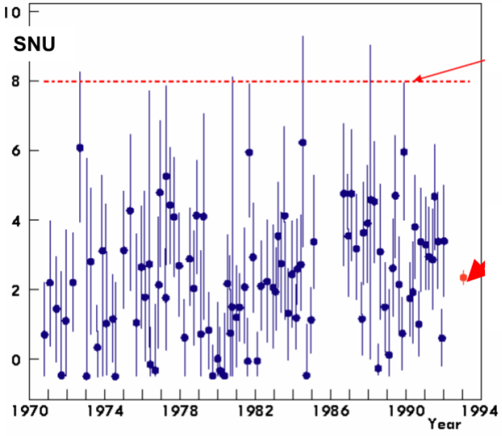
- 1 SNU (Solar Neutrino Unit) = 1 neutrino interaction / (s x 10^{36} target nuclei).

Homestake experiment

- Pioneering radiochemical experiment operating through 30 years: 1969 – 1999 by Raymond Davis Jr.
- 615 ton of C_2Cl_4 in the tank in the old gold mine Homestake in South Dakota
- Challenging and time consuming experiment – every 2-3 month ^{37}Ar atoms were extracted from the tank and counted by looking at Auger electrons emmitted during the Argon decay. 37Ar half-life = 35 days)
- Nobel prize for Davis in 2002



The chlorine experiment

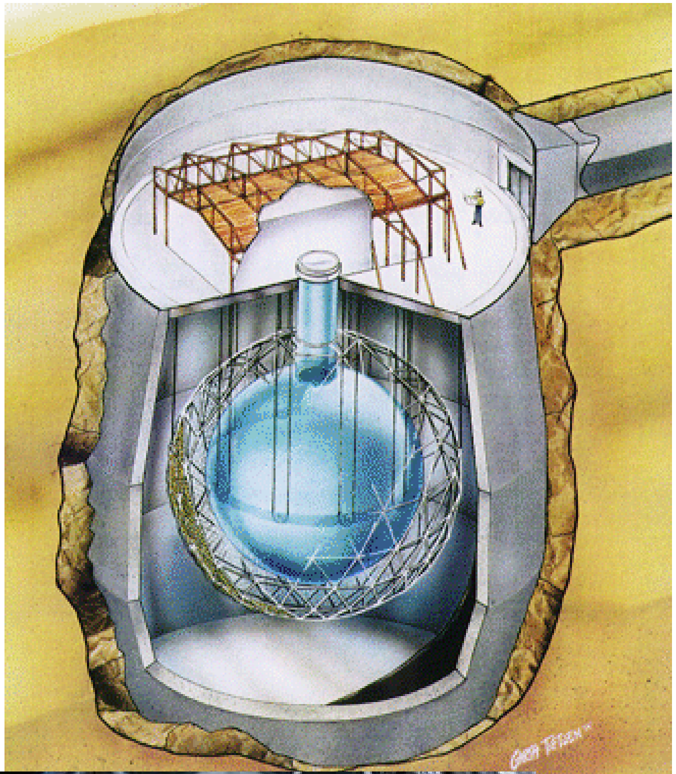


Predicted

Measured
By Homestake

Solar Neutrino Observatory (SNO)

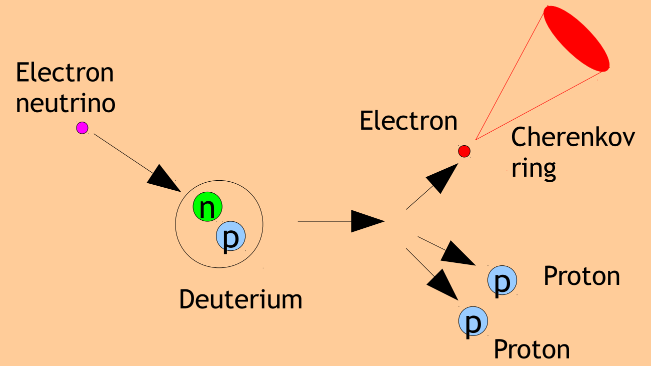
- 2000 meters underground in the nickel mine near Sudbury (Ontario, Canada)
- 1000 ton of ultra pure heavy water (D_2O) in the spherical tank with 12 meters of diameter
- 9500 photomultipliers detecting Cherenkov light (similar to Super-Kamiokande)
- Additional veto filled with water to get rid of the particles from radioactive decays.



Solar neutrino interactions in SNO

Charged Current (CC) interaction:

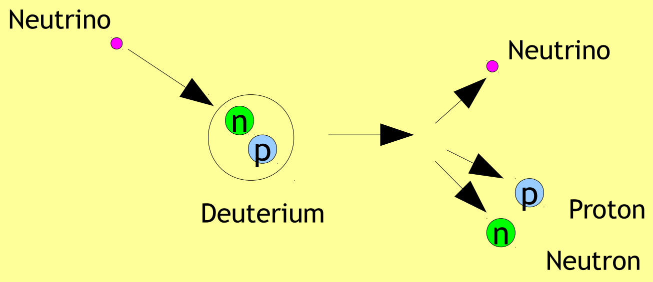
$\nu_e + d \rightarrow p + p + e^-$



Only electron neutrinos

Neutral Current (NC) interaction:

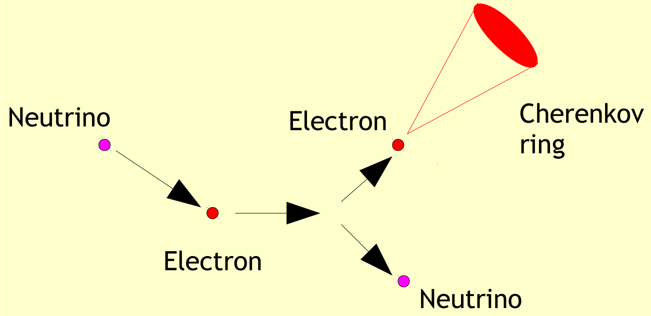
$\nu_x + d \rightarrow p + n + \nu_x$



All neutrino flavors

Electron Scattering (ES):

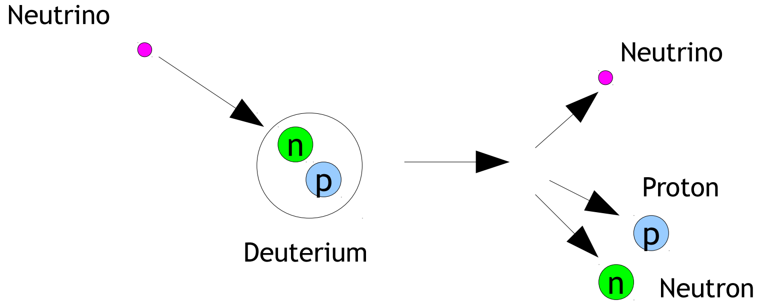
$\nu_x + e^- \rightarrow \nu_x + e^-$



All neutrino flavors
(but with different weights
- cross section different for
ν_e than for ν_μ, ν_τ)

NC interactions in SNO

- First phase: NC interactions in SNO are detected by measuring the photons from the neutron capture on deuterium:



$$n + {}^{2}H \rightarrow {}^{3}H + \gamma$$

Photon energy (γ): 6.26 MeV

- Second phase: 2 tons of NaCl were added to the detector tank and increased the NC detection efficiency from 24% to 84% (neutron capture on na chlorine)

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum \gamma$$

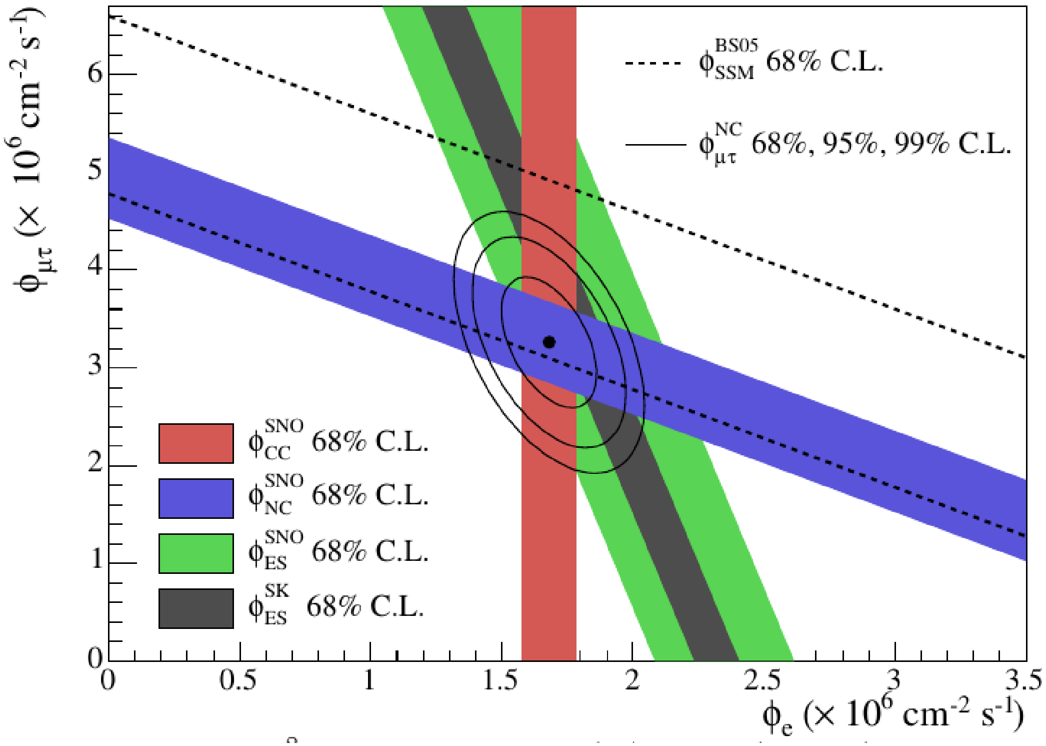
Energy of the photons ($\Sigma\gamma$): 8.58 MeV

- Third phase: helium counters were put into D_2O to estimate the systematic uncertainties for NC interactions independently:

$$n + {}^{3}He \rightarrow p + {}^{3}H$$

SNO - final results (2001 i 2002)

- By measuring CC and NC interactions simultaneously SNO experiment was able to calculate both the electron neutrino flux and the overal flux of all neutrino flavors.



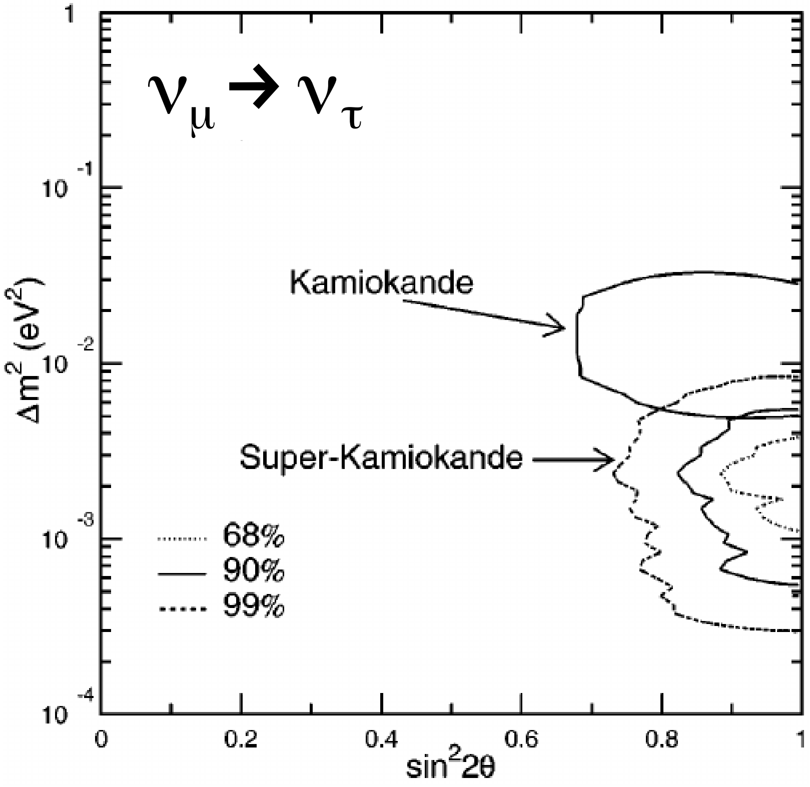
$$\Phi_{NC}=\Phi_{e\mu\tau} = 5.09 \begin{smallmatrix}+0.44\\-0.43\end{smallmatrix}(stat)\begin{smallmatrix}+0.46\\-0.43\end{smallmatrix}(sys)\times10^6\,cm^{-2}s^{-1}$$

$$\Phi_e = 1.76\pm0.05(stat)\pm0.09(syst)\times10^6\,cm^{-2}s^{-1}$$

$$\Phi_{Teor}=\Phi_{e\mu\tau} = 5.05\begin{smallmatrix}+1.01\\-0.81\end{smallmatrix}\times10^6\,cm^{-2}s^{-1}$$

Atmospheric neutrinos oscillations

- Atmospheric muon neutrinos oscillate – change their flavor on their way to the detector to taon neutrinos → the ratio of muon neutrinos to electron neutrinos is different than predictions
- The longer source-detector path the more muon neutrinos disappear → dependence on the zenith angle
- Based on the measurements Super-Kamiokande experiment calculated the corresponding mass splitting and the mixing angle from the PMNS model.



$$\sin^2 2\theta > 0.82 \qquad 90\%\,C.L.$$

$$5\times10^{-4} < \Delta m^2 < 6\times10^{-3}\,eV^2$$

Results confirmed later by a number of experiments:
K2K, MINOS, T2K, OPERA ...

Solar neutrinos puzzle solved

- In the Sun only ν_e are produced. Electron neutrinos on their path from the sun to the earth change their flavor into muon and taon neutrinos.

- SNO showed: $\nu_e \rightarrow \nu_\mu , \nu_\tau$
  - Electron neutrino flux is ~1/3 of the total neutrino flux, because electron neutrinos transform into ν_μ i ν_τ
  - Total neutrino flux from the Sun agrees with SSM

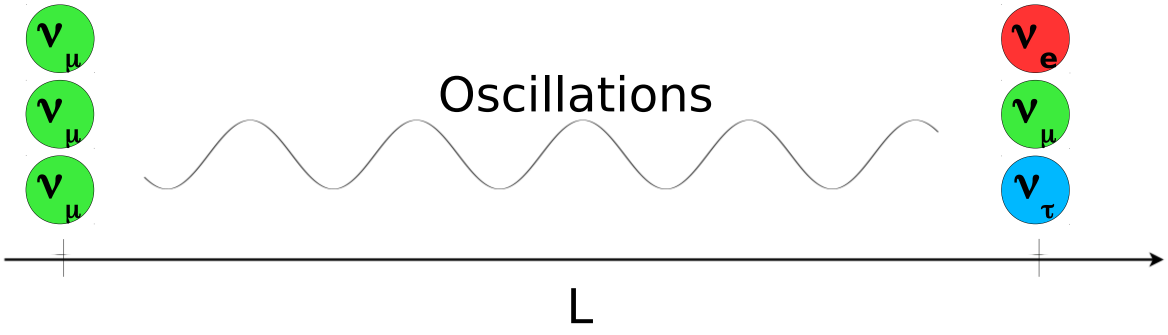
- Homestake, GALLEX/GNO, SAGE were measuring only electron neutrinos. ν_μ and ν_τ were not detected → deficit.

$$\nu_e + {}^{37}Cl\left({}^{71}Ga\right) \rightarrow {}^{37}Ar\left({}^{71}\mathrm{Ge}\right) + e^-$$

- Kamiokande and Super-Kamiokande were measuring total neutrino flux but with different weights → deficit.

Neutrino mixing

- Neutrinos oscillate – change their flavor with time. Experimentally confirmed by a number of experiments: Super Kamiokande, K2K, SNO, KamLAND, MINOS, Daya Bay, T2K,...



Muon neutrinos
with energy E

Oscillations

Detector
(neutrinos of
all three flavors)

L

- Neutrinos are produced and detected via weak interactions (flavor eigenstates) but propagate in space as the linear superpositions of the mass eigenstates.

Mixing matrix

Flavor eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass eigenstates

- Probability of the transition $P(\nu_\alpha \rightarrow \nu_\beta)$ depends on mixing matrix elements U_{PMNS} (unitary 3x3 matrix) and on **$\sin^2(\Delta m_{ij}^2 L/E)$**, where $\Delta m_{ij}^2 = m_i^2 - m_j^2$

Neutrino oscillations

Flavor eigenstates

Pontercorvo-Maki-Nakagawa-Sakata matrix (U_{PNMS})

Mass eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij}=\cos\theta_{ij}$

$s_{ij}=\sin\theta_{ij}$

$$P(\nu_\alpha\rightarrow\nu_\beta)=\delta_{\alpha\beta}-4\sum_{i<j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\cdot\sin^2\Phi_{ij}\pm2\sum_{i<j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\cdot\sin^2\Phi_{ij}$$

$$\Phi_{ij}=\Delta m^2_{ij}\frac{L}{4E_\nu}=1.27\cdot\Delta m^2_{ij}[eV^2]\cdot\frac{L[km]}{E_\nu[GeV]}$$

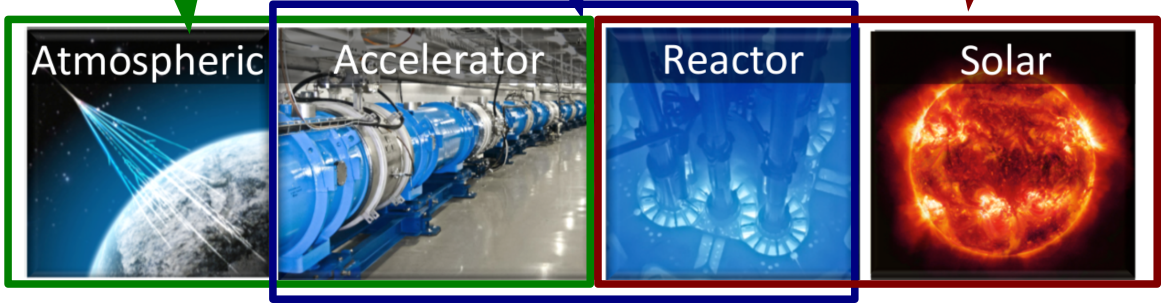
- Transition probability $P(\nu_\alpha\rightarrow\nu_\beta)$ depends on:
  - 3 mixing angles: θ_{23}, θ_{13}, θ_{12}
  - 1 complex phase: δ_{CP}
  - 2 independent mass splittings: Δm^2_{32} , Δm^2_{12}
  - Detector-source distance (L), neutrino energy (E) – chosen experimentally

PMNS model parameters

Neutrino oscillations - measurements

$$U_{PMNS}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot$$

Majorana phases



ν_μ **disappearance**

ν_e disappearance,

$\bar{\nu}_e$ disappearance

ν_e **appearance)** , $\bar{\nu}_e$ disappearance

ν_e appearance

$$P(\nu_\mu\rightarrow\nu_e)\simeq\sin^2\theta_{23}\sin^2\boxed{2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$
$$-\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\left(\frac{\Delta m^2_{21}}{4E}\right)\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\boxed{\sin\delta_{CP}}+\ldots$$

ν_μ disappearance

$$P(\nu_\mu\rightarrow\nu_\mu)\simeq 1-4\cos^2\theta_{13}\boxed{\sin^2\theta_{23}}[1-\cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\left(\frac{1.27\boxed{\Delta m^2_{32}}L}{E}\right)$$

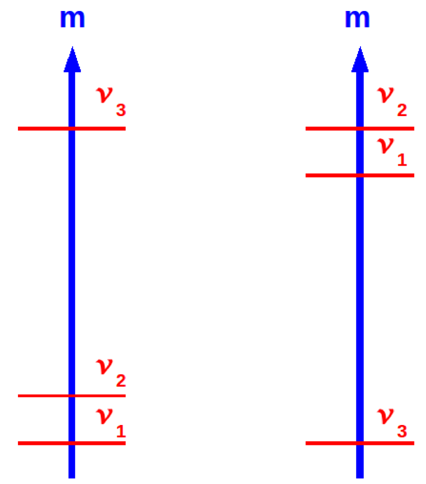
Neutrino oscillations state of art

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.547 \pm 0.021 \quad \text{(Inverted order)}$$
$$\sin^2(\theta_{23}) = 0.545 \pm 0.021 \quad \text{(Normal order)}$$
$$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Inverted order)}$$
$$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Normal order)}$$

$$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$$
$$\delta,\ CP \text{ violating phase} = 1.36 \pm 0.17\ \pi \text{ rad}$$

- Open questions:
  - What is the value of δ_{CP}? CP symmetry violation in neutrino sector?
  - Value of θ_{23}? If not 45 degrees, then which octant?
  - What is the neutrino mass ordering? Normal: $\mathbf{m_3>m_2}>m_1$ (NO) or inverted: $m_2>\mathbf{m_1>m_3}$ (IO)?
  - Sterile neutrinos?
  - Absolute neutrino masses?
  - Dirac or Majorana particles?

Neutrino mass ordering



Normal
Ordering
NO

Inverted
Ordering
IO